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SOME IDEAS ON THE CONTROL OF NEAR-WALL EDDIES

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Near Wall Eddies

by

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Abstract

The near-wall region of bounded turbulent flows consists of streamwise vortices, low speed streaks, intense shear layers, inflectional velocity profiles, oscillations and ejections of low speed fluid out into the logarithmic layer. A mass of data has accumulated over the past 25 years concerning this important chain of events, however the general picture is still rather suggestive rather than conclusive. Some proposals are offered as means of interacting with and/or interrupting the sequence of these events in the wall region.

Wall layer structure

The eddy structure near the wall in bounded shear flows has usually been referred to as the "bursting sequence" or the "bursting phenomenon".[1] This series of events, depicted in figure 1, indicates their sequence of occurrence as discussed below. It is suggested that there may be a feed back mechanism between the large scale outer eddies in the shear flow and the wall layer events which may be important in attempts to manipulate this structure.

Streamwise Vortices

The existence of streamwise vortices in the near wall region has been conjectured by many authors. In its simplest hypothetical case, these vortices appear as vortex tubes aligned with the streamwise direction as sketched by Blackwelder(1978). Kline et al.(1967) assumed such vortices existed within the flow field. Kim et al.(1971) showed some hydrogen bubble visualization photographs that had rotation consistent with streamwise vortices with the vortices inclined away from the wall. Bakewell and Lumley(1967) and more recently Aubry et al.(1988) used the proper orthoganal decomposition in the near wall region and determined that a pair of counter-rotating streamwise vortices containing largest amount of energy. Lee, et al. measured the velocity gradients on the wall and ascribed their results to alternating regions of streamwise vorticity. Blackwelder and Eckelmann(1979) measured the two stress components on the wall and found that the most probable stress pattern conformed to counter-rotating vortices also. Smith and Schwartz(1983) photographed hydrogen bubbles in the $y-z^2$ plane and found significant streamwise rotation in the wall region for $y^+ \leq 10$. They observed frequent counter-rotating structures and suggested that they were associated with the low speed streaks.

1. In the earliest research on the subject, this structure was referred to simply as a "burst" as in Kline et al.(1967). In view of our increased knowledge, it is more descriptive to use the term "burst" only as an adjective in describing this sequence of events.

2. The usual boundary layer coordinates of x,y and z with the velocity components u, v and w will be used in the streamwise, normal and spanwise directions, respectively.

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They concluded that rotating, streamwise structures do occur in the wall region and they often occurred in counter-rotating pairs.

The cumulative evidence from these researchers suggests that streamwise vortices inhabit the wall region although they do not necessarily occur in counter-rotating pairs. By using the velocity correlation in the wall region from direct numerical simulations, Moser and Moin(1984) have argued that since $R_{ww}(\Delta z)$ does not have a minimum at $y^+ \sim 30$, single vortices must be more predominant than counter-rotating pairs. Guezennec et al.(1989) have found that ω_x structures do not occur in pairs of equal magnitude. The vortices have diameters that grow from 10 to $40\nu/u_\tau$ and they migrate away from the wall during their lifetime such that their centers range from 10 to $50\nu/u_\tau$ from the wall. These vortices may be a part of a larger vortex structure, such as a hairpin or horseshoe vortex, that extends further into the logarithmic region; in which case, the streamwise vortices would be composed of some ω_y and ω_z as well as ω_x. No evidence is presently available to indicate the length of the vortices and their origin remains a mystery.

Low Speed Streaks

The low speed streaks(denoted as LSS) are the most ubiquitous aspect of the bursting process and were first studied by Kline et al.(1967). An experimental observation of the low speed streaks is shown in figure 2. The data were taken by a spanwise hot-wire rake at $y^+ = 15$ in a turbulent boundary layer. The time record from the twelve sensors has been converted to a streamwise spatial distance by Taylor's hypothesis to provide a continuous record over $0 < x^+ < 4000$. Constant velocity contours for $u(x,z) = k \cdot [U(y) - u_{rms}(y)]$ are plotted for $k = -1$ and -2. The lower speed fluid appears inside the elongated regions which have spanwise scales of typically $20\nu/u_\tau$ and streamwise scales of several hundred viscous scales. The VITA technique was applied to the same data and its detection locations are also indicated. Note that the technique picks up the strong shear layers at the sides of the streaks and has a preference for locations where there is a strong spanwise velocity. The significance of this observation is still under investigation. A similar plot of the streaks in figure 3a is from the numerical data of the Center for Turbulence Research/NASA Ames supplied by Robinson(1988). Moin and Kim(1982) showed that neither the v, w, nor the pressure had an elongated streaky structure anywhere in the wall region. However the ω_y vorticity displays a streaky structure due to its strong $\partial u/\partial z$ gradients as seen in figure 3b.

A simplified sketch of the low speed streaks is found in figure 4. The streaks are shown with equal spacing in the spanwise direction but in nature they have a random spanwise distribution. Also the streaks meander during their downstream migration. This motion has deliberately been eliminated to simplify the figure although may be important in the production of turbulence. Lee et al.(1974) found that their most probable spacing is $80\nu/u_\tau$ and their average spacing is $100/u_\tau$ very near the wall. Talmon et al.(1986) showed that their average width is only $20-40\nu/u_\tau$. Nakagawa and Nezu(1981) suggested that the spanwise spacing, λ_z, is lognormal and showed that the spacing increased as one approached the logarithmic region. In one of the more comprehensive studies of these eddies, Smith and Metzler(1983) found that the streaks persisted for $\Delta t^+ = 500$ on the average but times up to $2500\nu/u_\tau^2$ were observed. Even

with a moderate convection velocity of $5u_\tau$, this observation indicates that the streaks are several thousand viscous scales long. They also showed that the structure of the LSSs is independent of the Reynolds number over the range $700 < Re < 5800$ agreeing with the data compiled from different investigators by Hirata et al.(1982).

The origin of the streaks is still unknown. Assuming the streamwise vortices exist on the scales indicated above, their induced motion could be sufficient to explain the observation of the streaks. Since the streaks lie in a region of strong velocity gradient, the streamwise vorticity need not be very strong to create the streaks. An alternative suggestion is that the streaks are a manifestation of the strong shear in the wall region. Lee et al.(1987) showed that when homogeneous turbulence was subjected to a strong uniform shear comparable to that found in the wall region, low speed streaks resulted. This mechanism would also amplify the existing ω_x due to stretching and hence the streaky structure may still be associated with ω_x eddies. Streaks have also been observed by Nakagawa and Nezu(1981) and Smith and Metzler(1983) to merge and divide in the wall region, however this happens infrequently and can not be considered as a generation mechanism. Chu and Falco(1988) have suggested that small eddies moving toward the wall may generate the LSSs.

Lift-up of the LSSs

At some point in the bursting process, the low speed streaks are lifted up away from the wall. This is described by Kline et al.(1967) as a gradual process during which the streaks marked with hydrogen bubbles appear to become thinner as they move away from the wall. Based upon motion pictures of the flow, they suggest that the lift-up is a result of streamwise vorticity. When following a marked streak downstream, it is observed that the slow outward drift suddenly become more rapid and is a precursor to the oscillations discussed below. This lift-up was defined by Kim et al.(1971) as the first stage of the dynamical bursting process and that it typically created an inflectional U(y) profile. They also suggested that it leads to an instability such as the inviscid one described below.

Intense Shear Layers and Inflectional Profiles

Once the low speed streaks are present, they are surrounded by a shear layer and inflectional velocity profiles. Since the streaks are indeed low speed fluid, they have relatively higher speed fluid on both sides in the spanwise direction and there is obviously higher speed fluid above them as sketched in figure 4. Since there is no mean gradient in the spanwise direction, the existence of the LSSs implies that there will also be an inflectional velocity profile in the spanwise direction as seen in the sketch. When the spanwise velocity gradient was plotted as in figure 3b, it was almost identical to the normal vorticity component. Hence figure 3b indicates the location and magnitude of the spanwise shear layer. Because of the mean gradient in the normal direction, the LSS can exist without an inflectional U(y) profile. However Blackwelder and Swearingen(1989) have shown that inflectional profiles occur as often in the normal as in the spanwise direction and found that it was almost impossible to observe an instantaneous velocity profile anywhere in the wall region without an inflection point.

Since inflectional profiles are inviscidly unstable and hence important in any control problem, it is an interesting exercise to ask where the loci of the inflection points lie. Often the inflectional characteristics are thought of as occurring at a point (i.e. an inflectional point) although this concept must be extended in the three dimensional case. In the classical one dimensional textbook case of $U(y) = \tanh(y/\Delta)$, the inflection point is indeed a point. Expanding this concept to a two dimensional flow shows that the inflections lie along a line. In a three dimensional flow as in the wall layer, the inflections lie on a surface. That is, the loci of the points where the derivative $\partial^2 U/\partial\alpha^2 = 0$, where α is any direction, prescribe a surface in the three dimensional space. (Of course one can also examine the inflectional characteristics of the other velocity components as well and find other surfaces.) If the higher speed fluid above the LSSs has become inflectional, the LSSs

will be enveloped by an inflection surface. Thus it is useful to think of this surface as surrounding the low speed regions of fluid. The stochastic nature of the flow indicates that the inflectional surfaces are random in space and time. Of course the surfaces can end in the fluid where the inflectional profiles no longer exist.

The inflectional U(y) profiles have been observed by many investigators. Kim et al.(1971) found that the U''(y)=0 was a common feature of all cases of lift up observed. Willmarth and Lu(1972) found that the bursting phenomenon occurred when the velocity profile first became inflectional. Grass(1971), Kline et al.(1967), Blackwelder and Kaplan(1976) and others have concurred.

An Instability Mechanism and Oscillations

The importance of the inflectional profiles is that they seem to set up the necessary conditions for an inviscid Kelvin-Helmholtz instability within the fluid. Michalke(1965) has analyzed this problem in detail for the hyperbolic tangent profile with a spatial scale of Δ. He found that the most rapidly growing disturbance had a wavelength of 14Δ and the growth rates of the linear instability are extremely large. Michalke's results apply to a flow field that is parallel, steady and two-dimensional, but Blackwelder and Swearingen(1989) have shown that these constraints are satisfied for the inflections within the wall region. Another factor that could influence the results from Michalke's theory is the proximity of the wall. Huerre(1983) has shown that Michalke's results are unaffected as long as the wall is more that 1.2Δ away from the wall. Nishioka et al.(1980) support this result.

The inflectional instability will produce a growing disturbance with a wavelength of approximately 14Δ according to Michalke. The difficulty is that if the disturbance grows as fast as Michalke predicts, its amplitude will increase by 36 and its energy by more than 1000 while it travels only one wavelength downstream! Thus in a turbulent flow environment where the background disturbance level is large, it is not evident that more than one wavelength will be observed. Even if it were possible, the nonlinear effects may distort the disturbance to a point of nonrecognition.

The length scale, Δ, of the inflectional profiles is roughly $10\nu/u_\tau^2$ according to Blackwelder and Swearingen(1989) and thus the wavelength of the oscillations should be approximately $150\nu/u_\tau^2$ for a Kelvin-Helmholtz instability. Wave lengths in this range have been observed by Kline et al.(1967), Kim et al.(1971), Emmerling(1973), Bacher and Smith(1985), Oldaker and Tiederman(1977), and others. These oscillations are believed to develop into ejections at a slightly greater distance downstream as discussed below. This oscillation is distinct from the bursting frequency as seen later.

Ejections

The next stage of the bursting process is a more rapid outward movement of a small low speed parcel of fluid called an ejection by Corino and Brodkey(1969). They stated that the ejections were $20-40\nu/u_\tau$ long in the streamwise direction and were $15-20\nu/u_\tau$ in the spanwise direction and originated at $5 < y^+ < 15$. They appear to move away from the wall with an angle of approximately $8°$ and were skewed from the downstream direction an average of $15°$ in the x-z plane. Since the ejections are low speed fluid moving away from the wall, they contribute significantly to the Reynolds stress in the near wall region. Above $y^+ \approx 15$, they are the primary contributor to the uv shear stress whereas the sweeps have been found to be the main contributors to the shear stress below $15\nu/u_\tau$.

The ejections originate from a lifted portions of the LSSs and have been studied in detail by Bogard and Tiederman(1986). They found that single or multiple ejections occurred within a short time interval as reported previously by Corino and Brodkey(1969) and Willmarth and Sharma(1984). Oldaker and Tiederman(1978) have shown that when an ejection occurs, it is often preceded by an oscillation upstream. The oscillations appear to be a result of the inflectional profile. Since the growth rates are so extremely

rapid, the wave train of the oscillations may be quite short; i.e. only one or two crests may be observed as sketched in figure 5. These crests are believed to have developed from the initial disturbances that had a length scale corresponding to the most amplified wave. The most amplified part of the wave moves away from the wall thus forming an ejection as suggested in figure 6. This strong outward motion may be due to non-linear effects, interaction with the wall or other unknown reasons. This idea suggest that when multiple ejections occur, they would originate from the same LSS since it is unlikely that two adjacent streaks would have the same growth rates due to the randomness of the motion in this region. By combining visual and transducer techniques, Bogard and Tiederman found that the multiple ejections do indeed originate from the same streak. Moreover, Bogard(1987) found that when multiple ejections occurred, the mean spacing between them was $225\nu/u_\tau$ consistent with the length of the oscillations discussed above.

Breakup

Breakup[3] is the last phase of the bursting process and terminates the coherent aspect of the phenomenon. Breakup is often defined from the visualization studies and is described as the loss of the Lagrangian marker in the fluid. Of course this definition just states that *it is impossible to follow the motion further* and hence does not describe the motion itself. It appears that after the ejection, the mixing is so rapid with the higher speed fluid that all evidence of coherent motion vanishes.

The breakup of the motion occurs in the region $20 < y^* < 50$ and results in the loss of the coherent motion of the ejections. Since more than one ejection may occur from the same streak, breakup includes the termination of multiple ejections. Smith and Metzler(1983) found that the ejections and breakup are not the end of the LSS, but rather a residual amount of low-speed fluid remains near the wall that provides the seed for or grows into a LSS downstream. Hence each streak may have more than one breakup associated with it.

Bursting Frequency

The bursting frequency refers to the average number of occurrences of a specific event per unit time in the near wall region. The specific event is often the breakup in the visualization investigations and is the output of a detection algorithm in the transducer studies. Hence care must be exercised when comparing the bursting frequency obtained by different methods. The bursting frequency yields the significant time scale of the flow essential for intermittent control schemes.

The scaling of the bursting frequency has been one of the more controversial topics associated with the bursting process. Unfortunately the scaling and its magnitude is one of the most important parameters in the control process. The earlier work of Kline et al.(1967), Kim et al.(1971) and others indicated that the breakup frequency scaled with the wall variables. However Rao et al.(1971) indicated that the outer scales correlated the detection frequency over a decade of Reynolds numbers for data taken from a fixed length hot-wire. Blackwelder and Haritonidis(1983) showed that as the Reynolds number increased, the nondimensional scale of the probe became large compared with the scale of the ejections and hence the spatial averaging of the probe led to incorrect results. When different hot-wire probes were used such that the nondimensional scale of the sensors remained constant as the Reynolds number increased, the detection frequency scaled with ν and u_τ and remained constant. This scaling appears to be universal for pipes, channels and turbulent boundary layers as long as the boundary is sufficiently smooth. This result has been confirmed with transducer techniques by Chambers et al.(1983) in accelerating channel flows, Shemer and

Haritonidis(1984) in pipe flows and Willmarth and Sharma(1984) in a turbulent boundary layer. Kim and Spalart(1987) found similar results with numerical turbulent boundary layer data. Luchik and Tiederman(1987) using hot-film data and Tiederman(1989) with LDA data concluded that inner scaling was correct in channel flows. On the other hand however, Alfredsson and Johansson(1984) have proposed a mixed scaling for detections using a hot-film in a channel flow for Reynolds numbers of $1.3\cdot10^4$ to $1.2\cdot10^5$ based on the half channel width. Shah and Antonia(1989) have supported this conclusion for higher Reynolds numbers and caution that the inner scaling may be valid only in the range where low Reynolds number effects are known to be important. This important question needs much more study and clarification.

Pockets, Sweeps and High Speed Regions

Another aspect of the wall layer eddy structure is the bombardment of this region by regions of higher speed fluid that originate in the outer area of the shear flow. These high speed regions were first noticed by Corino and Brodkey(1969) who characterized them as sweeps of high speed fluid moving essentially parallel to the boundary but with a small velocity component inclined toward the wall. This motion usually terminated a breakup and left the flow in a relatively quiescence state. The sweep was a larger scale motion than the ejection in the x-y plane but due to experimental limitations, they cound not ascertain the extent of the sweep in the spanwise direction.

The higher speed regions are inherently more difficult to study visually because they originate in the logarithmic and outer regions and it is difficult to place a Lagrangian marker into this region without additional disturbances. Falco(1980) has overcome this handicap by injecting large amounts of marker through the wall. With small amounts of injected smoke, he observed LSSs similar to those of Kline et al.(1967). With higher concentrations, the wall layer was filled with smoke for several hundred viscous scales downstream. Under this condition, the most readily observed features were regions that became devoid of smoke due to strong high speed disturbances hitting the wall region and clearing it of the marker. Falco found these unmarked regions were typically $80-100\nu/u_\tau$ in diameter and named them pockets. Since they are a high speed disturbance of the wall region, they appear to be related to the sweeps discussed above. In a simulated boundary layer flow, Chu and Falco(1988) found that eddies originating in the outer region of the boundary layer do indeed produce pockets as well as the streaky structure in the wall region.

Reynolds Number Effects

One of the more perplexing unsolved questions concerning the bursting phenomenon is the role of the Reynolds number which will obviously be important in designing control schemes. Most all of the measurements and calculations of the structure have been at low Reynolds numbers in order to have sufficient resolution in the wall region, whereas the applications are typically at much higher Reynolds numbers. The law of the wall is assumed to be independent of the outer layer eddy structure and hence should be independent of the Reynolds number. A corolary to this argument suggests that the wall region of pipes, channel and boundary layers should be similar when scaled with the wall variables. Although these assumptions may be true to first order, as more data become available it appears that there is an influence of the Reynolds number on the wall structure. For example the recent results of Wei(1987) and Spalart(1986) have shown that shear stress has a strong Reynolds number effect at low Re_θ.

To study this problem from a different angle, McLean(1989) has analyzed the spanwise correlation structure of the streamwise velocity component. Figure 7 presents the $R_{uu}(\Delta z)$ two point correlations at a constant $y^*=15$ for $10^3 < Re_\theta < 10^4$. The data were all taken with hot-wire sensors that had a spatial resolution less that $25\nu/u_\tau$ as indicated in the figure. Two facts are immediately apparent. First, the only evidence of a strong negative region at $\lambda_z^* \approx 50$ is for the lowest

3. This aspect of the motion was originally called the "burst" by Kline et al.(1967) and was renamed the breakup phase by Kim et al.(1971).

Reynolds number. This feature is considered to be a fundamental attribute of the LSSs. Secondly, the integral scale is not a constant at this location which violates the idea of viscous scaling in the wall region.

To check this, the integral scales were computed and are shown in figure 8 versus the Reynolds number along with some similar data taken in an adverse pressure gradient. Also included are some numerical results supplied by Robinson(1988) and Utami et al.(1989). Figure 9 presents the same data scaled with the momentum thickness, θ, versus the Reynolds number. This clearly shows that 1) there is a strong Reynolds number effect below $Re_\theta \approx 3000$, 2) the spanwise integral scale is associated with the outer flow field for $Re_\theta > 3000$, and 3) the integral scale is not altered by the adverse pressure gradients. In a turbulent boundary layer, the wake region shows a similar effect; namely the wake parameter, Π, increases at low Reynolds number and becomes a constant for $Re_\theta > 3-5 \cdot 10^3$.

The lack of a negative region in the $R_{uu}(\Delta z)$ correlations in figure 7 does not suggest that the low speed streaks disappear at the higher Reynolds numbers. It does imply that the underlying eddy structure changes for $Re_\theta > 3000$. One possible change may be that the streak spacing becomes more random as the Reynolds number increases. Smith and Metzler(1983) have shown that the probability spacing of the streaks is lognormal with an average value of $100\nu/u_\tau$. If the standard deviation of the probability distribution increased as the Reynolds number increased, the streaks would appear more randomly in space. For example, if the standard deviation were very small, the streak spacing would be quite regular and the spanwise correlation would have a strong negative region as well as possibly a secondary positive and negative peak as seen for some low Reynolds number results. (In the limit of zero standard deviation, the correlation would be sinusoidal.) Increasing the standard deviation would reduce the secondary peaks and also the negative peak. Another means by which the correlation could be altered as in figure 7 is to add other eddy structures or to have other eddies occur more frequently as the Reynolds number increases. This increase in scales is known to occur as the Reynolds number increases, but it is not clear how it would affect the wall region.

Control

Sufficient information has been acquired about the eddy structures within the wall region that it has become possible to think about means of controlling them under certain circumstances. Control in this case means interfering with one or more of the different aspects of the bursting phenomenon in order to achieve a desired purpose. Some concepts studied extensively in the literature, such as polymer addition, have demonstrated that alteration of some aspects of the eddies, such as their length scales, are feasible. Other ideas such as Large Eddy Break Up devices, riblets and grooves, etc. are currently being studied. Since drag reduction has been one of the more elusive aspects of control, the following will focus on this point as it relates to bounded turbulent shear flows. Other aspects of turbulence control including some of the more exotic methods are reviewed by Bushnell(1983).

In the past, much of the effort in controlling drag in boundary layers has been devoted toward maintaining a laminar flow over the body. It should be noted that different methods must be used to maintain a laminar flow than to decrease the drag in a turbulent flow. For example, suction under a laminar boundary layer can alter the base flow and change the stability characteristics of the boundary layer in a favorable manner. However global suction under a turbulent boundary layer will increase the drag unless massive suction is used to remove the entire turbulent boundary layer. In the laminar case, suction is used to delay transition and thus keep c_f small; in the turbulent case, the skin friction is increased by limited amounts of suction and alternative methods are required to reduce it. From the fundamental viewpoint, Tollmein-Schlichting waves have no dynamical significance in turbulent boundary layers; consequently techniques that delay transition will not necessarily be successful in fully developed turbulent flows. Hence drag reduction methods in turbulent shear flows must concentrate upon controlling the eddy structures within such flows.

Philosophy of Control

The usual approach to boundary layer control has been to apply some external condition globally; i.e. the condition is applied everywhere within the flow field without regard to how it effects the individual eddies in the flow. To illustrate, consider the Karman vortex street behind a circular cylinder. To alter the shedding, an external condition, such as suction, can be applied in the vicinity of the separation region on the cylinder. Applying suction around the entire cylinder may achieve the same result, but with a much larger expenditure of energy. Similar results are probably true within the turbulent boundary layer; namely we need only apply the external conditions selectively, i.e. locally with respect to the eddy structure that one is attempting to control. Hence to alter the LSSs, the external condition need be applied only under or around the LSS and hence must have dimensions comparable to those of the streaks.

A second important criteria for control is the phase of the controlling parameter with respect to the eddy structure. Phase is used here in its traditional sense in the temporal domain. The spatial phase parameter is taken care of by the selectivity parameter discussed above. Just as suction need not be applied everywhere around the cylinder example above, it also need not be applied continuously in time either. Short bursts of suction having a duty factor of 0.2 or less may be sufficient to control the shedding of vortices. Of course the suction must be applied at the appropriate phase of the shedding process to have the desired effect. If the phasing is incorrect, the vortex shedding process could be enhanced instead of suppressed. This aspect is extremely important in the control of turbulent production within the turbulent boundary layer because it is well known that the production is a very intermittent and random process.

To date very few if any attempts by man to control the eddies in a turbulent boundary layer have used temporal phasing and spatial selectivity primarily because of our limited knowledge of the eddy structure and because of the practical problems that need to be surmounted. However it is interesting to speculate that nature possibly has accomplished similar results. Bechert et al.(1985) have proposed that the scales of fast sharks may offer a "streak cancellation mechanism" that inhibits the momentum exchange and thus decrease the turbulent shear stress. Close examination of fish scales reveal that their motion may be instrumental in the prevention of local separation and control of the boundary layer eddies. Birds may use feathers in an analogous manner to alter the eddies in their unsteady motions of flight.

To examine the local and instantaneous effects of some of these techniques, consider a rigid wall such that $u = w = 0$ everywhere along it. The Navier-Stokes equations on the wall are:

$$v_w \frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\left[\nu \frac{\partial u}{\partial y}\right] \qquad \text{1a}$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial y}\left[\nu \frac{\partial v}{\partial y}\right] \qquad \text{1b}$$

$$v_w \frac{\partial w}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\partial}{\partial y}\left[\nu \frac{\partial w}{\partial y}\right] \qquad \text{1c}$$

where u, v and w are the instantaneous velocity components in the x, y and z directions respectively, v_w is the normal velocity at the wall due to suction or injection, p is the pressure and ν is the kinematic viscosity. Implicitly included are roughness elements on the wall which alter the position at which the boundary conditions are applied. When the velocities are replaced by the usual Reynolds averaged quantities in a two-dimensional mean flow, the second and third equations are identically zero and the first one is valid for the mean

parameters. Cases involving wall motion, compliant coatings and density changes are not included in the above formulation but are covered by Gad-el-Hak(1989).

To show the explicit dependence of the temperature at the wall, the right hand terms can be re-written as:

$$v_w \frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{d\nu}{dT}\frac{\partial T}{\partial y}\frac{\partial u}{\partial y} + \nu\frac{\partial^2 u}{\partial y^2} \qquad 2a$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\frac{\partial^2 v}{\partial y^2} \qquad 2b$$

$$v_w \frac{\partial w}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{d\nu}{dT}\frac{\partial T}{\partial y}\frac{\partial w}{\partial y} + \nu\frac{\partial^2 w}{\partial y^2} \qquad 2c$$

The second derivatives in equations 2a&c could have been written in terms of the vorticity fluxes at the wall. Thus small amounts of suction/injection, heating/cooling or pressure modification by roughness elements can alter the ω_x and ω_z vorticity flux which could have a profound effect on the eddy structures in the flow. Alternatively a disturbance such as a pocket that has pressure gradients in the x and z directions will produce ω_z and ω_x vorticity respectively on a constant temperature non-porous wall.

Selective Control

Selective control indicates that the control device is designed specifically to operate selectively on one or more aspects of the bursting phenomenon. That is, it assumes that we have the ability to isolate a feature of the bursting process, say the low speed streaks, and alter them in a manner that reduces the drag, increases the mixing, etc. One can also think about applying the control device intermittently in time since many of the characteristics of the eddy structure occurs only intermittently. This would require more intelligence in the control device but may become feasible with future development. Thus the idea is to construct a "smart wall" similar to a porpoise's skin, shark's scale, bird's feather, etc. which in the past have been assumed to be able to control the boundary layer over them. In principle one would prefer passive devices, but at the present any device that could decrease the drag in an explicable manner would be welcome.

Ideally one wants to affect only that part of the eddy structure that causes drag; i.e. that which promotes a large gradient at the wall. At first glance, the most effective method would be to alter the high speed regions because the shear at the wall is much stronger under them than under the LSSs. However the dynamics of the eddy structures becomes important in deciding how to best decrease the shear at the wall. For example it may be more efficient to alter a related component of the eddy structure that indirectly affects the high shear region rather than decreasing the shear directly. In a turbulent flow, one often desires to decrease the mixing away from the wall as well. With some ingenuity, both goals may be accomplished simultaneously.

In the smart wall concept, an infinite number of sensors would be embedded that sense the attributes of the eddy structures deemed desirable for control. In principle, this information would need to be shared with the entire wall. But since the eddies develop primarily in the downstream direction only, the information would be shared with those downstream locations only. The eddies also spread in the spanwise direction with some characteristic angle, so each wall position should be able to share its measured flow parameters with all those positions lying downstream within a cone of some prescribed angle. It is also apparent that the near field locations are more important that those a great distance downstream since the eddy has a finite lifetime.

From an operational viewpoint, the system would correspond to figure 10 where there are a variety of inputs that one could vary that would affect the outcome of the eddy structure. Since the eddies must obey the Navier-Stokes equations, the inputs can only alter the parameters in the equations(i.e. viscosity) and the boundary conditions. If the frame of reference is assumed to convect with the eddy, then the feed back loop is actually a "feed forward" loop in which the eddy characteristics are communicated forward to the locations downstream. Some simple systems incorporating the above concepts have been used in laminar boundary layers undergoing transition by Liepmann and Nosenchuck(1982) and Milling(1981).

Polymeric Drag Reduction

The best example of classical control is the addition of small amounts of polymers near the wall which produce a large net drag reduction. The most readily observable effect of the polymers is to increase the length scale in the wall region, $l_\nu = \nu/u_\tau$, as a result of the reduction of the skin friction, $c_f = 2\cdot(u_\tau/U_\infty)^2$.

Lumley(1969) and Landahl(1977) have proposed two of the principal analytical models for polymer additives. Lumley's argument suggests that the eddy structure in the drag reducing flow remains similar to that without the polymers but the length scale is increased. Landahl assumes that the near wall has eddies similar to those discussed above and that the effect of the polymers is to increase the extensional viscosity. This stabilizes and dampens the inflectional velocity profiles resulting in a decrease in the mixing of the high and low speed regions and thus a smaller amount of turbulence production. Lumley and Kubo(1984) state that there is no contradictions between these two theories and both agree that the primary result of the polymers is to dampen the secondary disturbance that grows on the inflectional profile. It is interesting to note that the small change in the extensional viscosity caused by the polymers is thought to alter an inviscid instability.

Tiederman et al.(1985) found that the polymers were primarily active in altering the eddy structures over $10 < y^+ < 100$. They and others have found that the non-dimensional distance between the LSSs increases as the drag reduction increases. Fortuna and Hanratty(1972) have shown that the non-dimensional wall shear fluctuations decrease with the addition of polymers but the spanwise shear fluctuations decreased more causing them to argue for a non-isotropic viscosity effect. Luchik and Tiederman(1988) conclude that the basic eddy structure in the wall layer is the same as in non-drag reducing flows; only the scales have been changed.

Large Eddy Break-Up Devices

One of the favorite drag reducing mechanisms in the 80's has been large eddy break-up devices(denoted by LEBUs) employed in the outer region of turbulent boundary layers. These devices selectively operate on the large eddies in the outer region of the layer but alter the shear stress at the wall. The generic version of this device consist of thin ribbons or airfoils at a constant distance above the wall spanning the flow field. Typically one or two LEBUs are used in tandem for the most beneficial effects. This arrangement reduces the skin friction downstream of the devices by 10 to 30% but add some device drag. Net drag reductions between 5 and 10% have been reported at moderate Reynolds numbers. These results have been reviewed by Anders(1985), Wilkinson et al.(1988) and Anders(1989).

There is no universal agreement on the method by which LEBUs reduce the drag but several mechanisms have been proposed as outlined in the above reviews. All of the devices produce a reduced skin friction immediately downstream of the devices, but not all of them have a net drag reduction due to the added device drag. Anders(1989) has noted that all of the successful devices had a slower boundary layer growth downstream than did the non-manipulated boundary layer and concluded that the entrainment process was altered by the devices. Chang(1987) used temperature as a passive contaminant and found the mixing and entrainment were significantly reduced in the presence of the LEBUs. In the outer region, the intermittency region was confined to a smaller domain. Correlations showed that the devices decrease the scale of the large eddies and significantly alter the negative regions of the correlations important in entrainment. The LEBUs also introduce smaller scale eddies into the flow but Chang found that their effects decayed rapidly downstream before the peak c_f reduction occurs. This would suggest that LEBUs would have no drag reducing ability in a channel flow since there is no entrainment as found by Prabhu et al.(1988).

Roughness

One of the oldest methods that alters the drag is the use of roughness elements in the boundary layer. Roughness usually increases the drag, but not necessarily so. To appropriately discuss roughness elements, one needs to distinguish between drag due to pressure loss and that due to friction. A pressure loss is associated with the retardation of fluid in a wake of the roughness element whereas frictional loss is due to an altered shear stress at the boundary. For example, a three dimensional protrusion above a smooth surface will form a downstream wake and have an associated pressure loss at the Reynolds numbers of interest. A backward facing step is a prime example of an increased drag due to a pressure loss. A two dimensional roughness element aligned in the longitudinal direction will have no wake and no corresponding pressure loss (although it will alter the pressure distribution in the spanwise direction). Riblets are an example of this type of drag alteration. Such a change in the surface geometry will usually increase the frictional drag because of the increased area. In addition, increased frictional drag can occur by changes in the viscosity or the wall shear.

Usual roughness elements are three dimensional protuberances above a smooth wall and have both a change in the pressure loss and the frictional component of drag, although they may be dominated by primarily one or the other. The distinction between these two types of drag has not always been made in the literature, but it will be important when determining the effects of roughness on the bursting process. For example, k and d type roughnesses will alter $\partial p/\partial x$ and hence change the flux of ω_z at the wall according to equation 1a. On the other hand, longitudinal grooves and riblets may have a non-zero local $\partial p/\partial z$ associated with them that causes a different distribution of ω_x at the wall according to equation 1c.

The most definitive study of the effect of three dimensional random roughness elements on the bursting phenomenon is due to Grass(1971). He used two different size roughness elements and observed their effect with hydrogen bubbles. He found that the ejections seemed to originate between the roughness elements and not over them. However once the ejections began, they appeared to be the same for both the rough and smooth walls. The LSSs did not appear, probably because the roughness elements protruded away from the wall to y+=10-15 and inhibited their development. Thus this provides a case where the LSSs were not a part of the bursting process and were not necessary to the development of eddy structure downstream. Possibly the wakes of the elements provided the low speed regions from which the ejections arise. In this case, the ejections would occur behind the elements rather than over them which would agree with Grass' observations. The laminar flow behind a single roughness element has been studied by Acalar and Smith(1987). The downstream wake had inflectional profiles similar to those discussed earlier. When combined with Grass' observation, this suggests that the inflectional profiles are a more fundamental element of the bursting process than the LSSs. Acalar and Smith observed horseshoe vortices that formed with a streamwise spacing corresponding to the most unstable wave of the inflectional profile.

Riblets are a more orderly form of roughness elements which consist of longitudinal grooves with various cross-sectional geometries. Walsh and his colleagues at NASA-Langley(see Walsh 1983) have tested many different groove geometries and found that the optimum shapes for drag reduction have a sharp peak protruding into the flow and have a height and spanwise spacing of typically $15\nu/u_r$. Drag reductions up to 8% have been obtained on the most popular triangular shape in favorable and adverse pressure gradients and with yaw angles up to 15° as reported by Wilkinson et al.(1988). In a separate study, Wilkinson and Lazos(1987) tested thin element riblets which used U shaped cross sections instead of the V grooves. They found a maximum 5-8% drag reduction and observed that for spanwise spacings less than 50 ν/u_r, the location of the u_{rms} maximum increased to y*≈35 instead of 15 for the smooth plate value. This suggests that the turbulent producing eddies were displaced further from the wall. Since the diameter of the streamwise vortices is typically 10-40ν/u_r, the smaller scale of the thin element riblets may have precluded them from operating near the wall and displaced them to a position above the elements.

The most surprising aspect of riblets is not that they reduce the drag slightly, but that they do not increase the drag dramatically. They have a wetted surface area that is up to 100% larger than a smooth surface which would suggest that the frictional drag would be correspondingly larger. Hooshmand et al.(1983) have shown experimentally that the drag is reduced up to 40% in the valleys which is offset by a 10% increase near the peaks. Similar results were found analytically by Bechert and Bartenwerfer(1986). Thus a net drag reduction results for the optimum riblet spacing; for non-optimum values, the drag increases. Just how this effects the eddy structure is not presently clear. It is an interesting observation that the optimum spacing does not correspond to the average spacing of the LSSs, hence the riblets are apparently not locking the LSSs into a fixed spanwise location. However the riblets may be inhibiting the rotation of the streamwise vortices and hence suppressing the formation of the low speed streaks. Bacher and Smith(1986) found that the riblets increased the spanwise spacing of the LSSs by 40%. Since small concentrations of polymers also increase the spanwise spacing of the LSSs, a similar mechanism may be evident with the riblets. Alternatively the riblets may reduce the meandering of the low speed streaks which could be important if the spanwise velocity component participates in the energy production.

Another type of roughness element was introduced by Johansen and Smith(1986). They used cylindrical rods of 4ν/u_r in diameter aligned in the streamwise direction over the entire flat plate. The longitudinal roughness elements (denoted by LREs) acted as nucleation sites for the formation of the low speed regions. For y*<10, these LREs reduced the meandering of the LSSs such that the streaks were always close to one of the elements. Thus the probability of finding a streak at a particular location was greatly improved. This control method is quite important if one wants to modify the LSSs which usually appear randomly in space and time.

Combined Roughness and Suction

Some newer methods of drag control are using combined roughness and suction to take advantage of the additional information of the eddy structure. Gad-el-Hak and Blackwelder(1987) generated hairpin eddies in a laminar boundary layer. By applying suction downstream, the eddies could be removed without tripping the boundary layer into transition. They also found that the same results could be achieved by an intermittent use of suction that was appropriately phased with the passage of the eddy.

The LREs have been used by Roon and Blackwelder(1989) in a method called selective suction. They used the roughness elements to anchor the streaks into known locations. As Johansen and Smith(1986) had found earlier, the LSSs were closely associated with the longitudinal elements below y*≈10. Figure 11 shows that above each of the LREs, the mean velocity was reduced by 1.5 - 2.0u_r at y*≈12. This results from the elevated no slip condition on the LREs and supports the results that the LSSs were less random. The number of streaks observed by an algorithm that determined the amount of time the velocity was below a fixed threshold decreased considerably. Even when the threshold was adjusted for the new local mean and rms values, the detected number of LSSs was reduced as seen in figure 12.

This configuration alone increases the drag slightly according to Johansen and Smith(1986). Small amounts of suction have been applied selectively under the streaks by masking portions of the porous plate between the LREs. The suction increases the net drag as manifested by the increased mean velocity at a fixed elevation above the wall as seen in figure 11. However the intent of the suction was to prevent the LSSs from lifting and forming the ejection phase of the motion which should reduce the turbulence production downstream. A measure of this activity is shown in figure 13

in which the shear layer detection frequency obtained by the VITA technique was measured. The detection parameters were not altered from those used on the flat plate. The detection decreased slightly when the LREs were added and decreased further with the suction. The combinal decrease in figure 13 is 20-30% suggesting that this method may offer some means of control of the near wall eddies.

To provide for a zero mass flow system, the fluid removed from beneath the LSSs could be added back into the wall region beneath the higher speed regions. This selective injection would reduce the gradient at the wall in those regions resulting in further drag reduction at the expense of a more complex system. Ideally the suction needs to be only applied when a lift up or ejection is occurring from a LSS. To adapt this method to the wall layer would require additional geometrical constraints or some intelligence to determine when the suction should be applied. Thus a more complex system would be necessary but with a reduced expenditure of energy.

Wilkinson et al.(1988) have tested a similar model using widely spaced riblets with suction and/or injection at the peaks of the riblets. They found that the suction through the riblet peaks yielded the same amount of drag as the equivalent suction on a flat plate. Injection of fluid through the riblets provided poorer drag results that injection through a porous plate. These results indicate that no selective effect was occurring with the riblet geometry and additional phasing information would be required to be successful.

Other Combined Methods

Equation 2 above indicates a correspondence between heating/cooling and suction/injection. In water, heating decreases the viscosity and promotes a negative temperature at the wall; thus $d v/dT \cdot \partial T/\partial y$ is positive. Hence the effect of heating at the wall is similar to suction; namely they both have a multiplicative effect on the velocity gradients. Instead of selective suction in water, selective heating could be used in or around the LSSs. However the results may not be the same because the heating also effects the magnitude of the viscosity and will alter the viscous terms in equation 2. This should also alter the vorticity flux of both ω_x and ω_z at the wall. The change in viscosity may also alter the mixing in the buffer and logarithmic regions as well. Thus a study of selective heating and/or cooling could be profitable.

An alternative method to control the turbulence within a boundary layer is to add another eddy structure that interacts with the existing eddies in a favorable manner, called eddy substitution by Wilkinson et al.(1988). In the outer region of the turbulent boundary layer, Gad-el-Hak and Blackwelder(1987) utilized an upstream facing slot jet to organize the turbulence into large scale intermittent eddies. The eddy size and passage frequency could be controlled by the jet velocity and intermittency. Near the wall, various techniques can be used to introduce new eddies that could be controlled. Since the longitudinal roughness elements of Johanson and Smith(1986) organize the LSSs near the wall, LREs of finite streamwise length but staggered in the spanwise direction may cause new streaks to form that would extract energy from the older streaks thus preventing their eruptions into ejections. Similar ideas have been pursued with three-dimensional riblets at NASA-Langley(Wilkinson 1988). Small scale delta winglets, possibly modelled after fish scales, could generate trailing streamwise vortices that could interact with existing vortices or be cancelled out downstream by other winglets.

Conclusions

The control of the eddy structures within the boundary layer is still in its infancy. The large amount of information accumulated during the last twenty years on the eddy dynamics within the turbulent boundary layer has opened the door to the concept of selective control that suggests that the eddies may be controlled directly rather than applying global techniques. Ultimately this may lead to more efficient devices for control of these eddies but such methods are still many years away from practical application.

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SEQUENCE OF THE BURSTING PROCESS

Figure 1. The sequence of events comprising the bursting process.

Figure 2. Iso-contours of the streamwise velocity component at $y^*=15$ in a turbulent boundary layer. The VITA detection locations are denoted by the solid squares.

Figure 3. Iso-contours of the streamwise velocity component, u(above) and the normal vorticity, ω_y(below). The low speed streaks are denoted by the solid lines. The iso-contour levels are $2u_\tau$ for u and $0.2v/u_\tau^2$ for ω_y. This data is from the numerical data base computed by P. Spalart at the Center for Turbulence Research/NASA Ames for a boundary layer at Re =670 at y+=15.
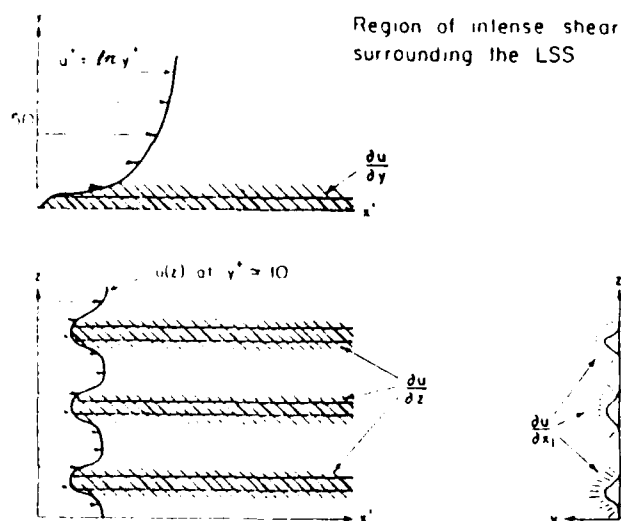
9

Figure 4. Sketch of the low speed streak (shaded areas) showing the regions of intense shear surrounding the low speed fluid. The inflectional surface is embedded within the strong shear region.
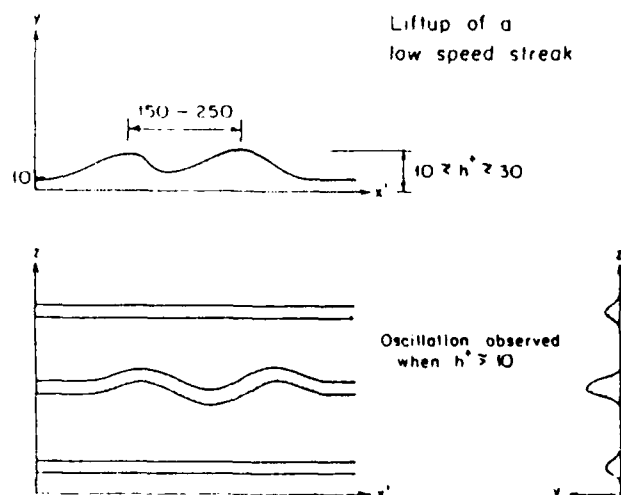

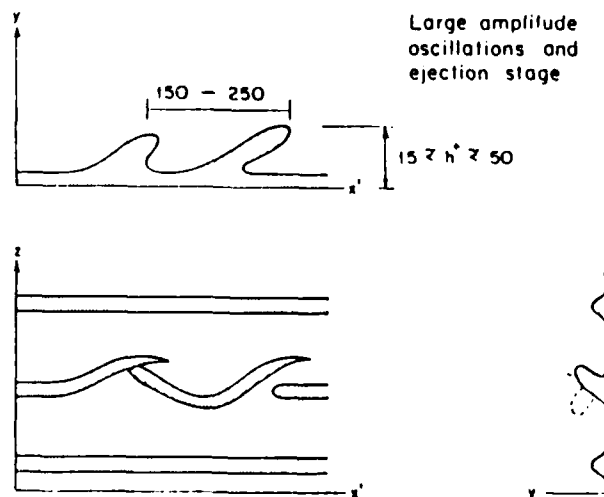Figure 5. Sketch of the lift-up of a portion of the LSS.

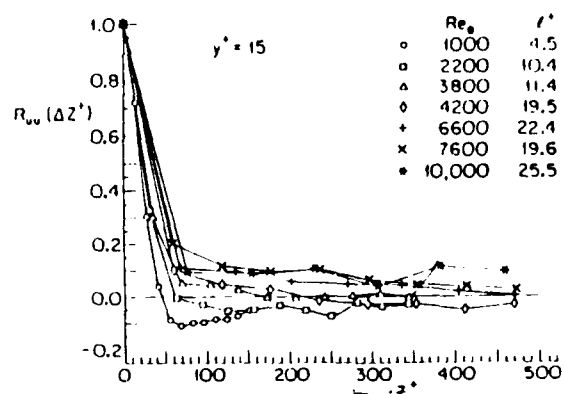Figure 6. Continuation of the lift-up phase of the LSS and the formation of the ejection.

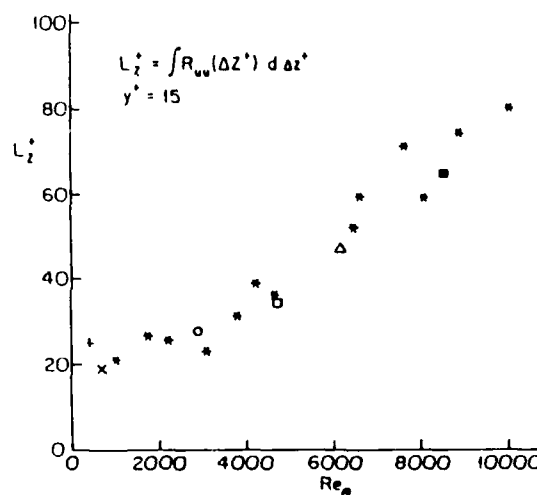Figure 7. Correlations of the streamwise velocity component in the spanwise direction at different Reynolds numbers. The sensors lengths are indicated.

Figure 8. The spanwise integral length scale at $y^+=15$ versus the Reynolds number(symbols are given in figure 9.)
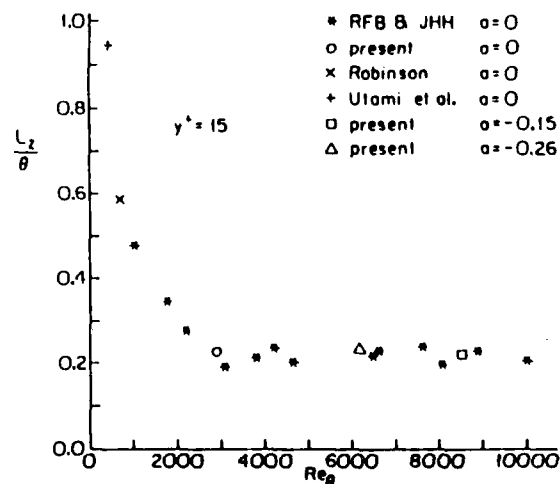
Figure 9. The spanwise integral length scale at $y^+=15$ normalized with the momentum thickness versus the Reynolds number. The adverse pressure gradients have $U(x) \sim x^a$.
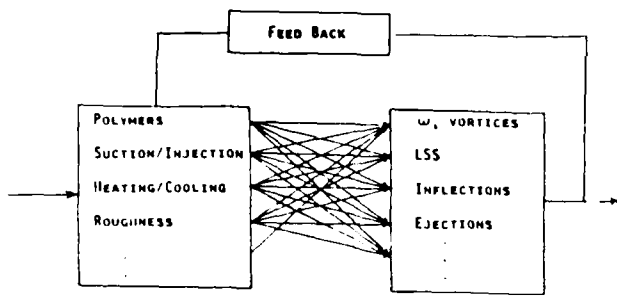
10

SELECTIVE CONTROL

Figure 10. Schematic of a selective control mechanism whereby several different techniques can be used to operate upon the turbulent eddies.
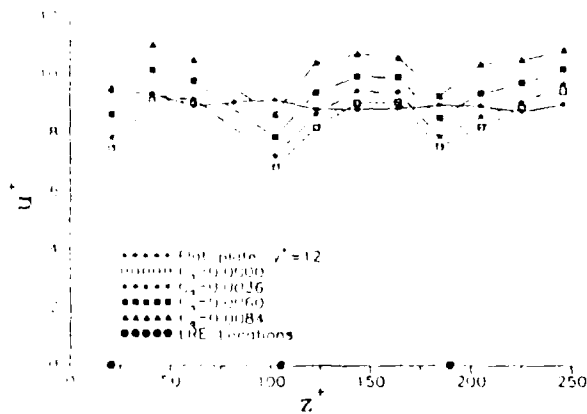

Figure 11. Spanwise velocity profiles for the flat plate, with the longitudinal roughness elements and suction.
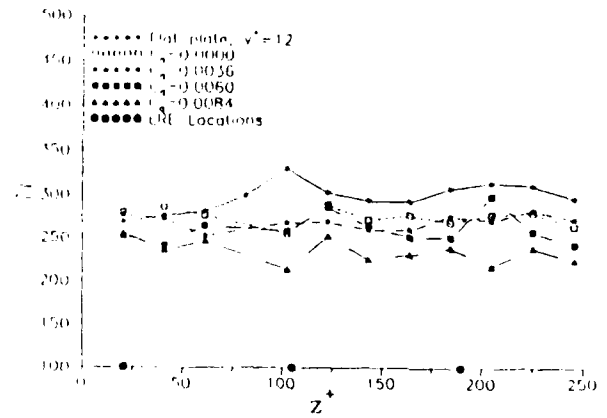

Figure 12. The number of detected LSSs with the longitudinal roughness elements and suction across the span.
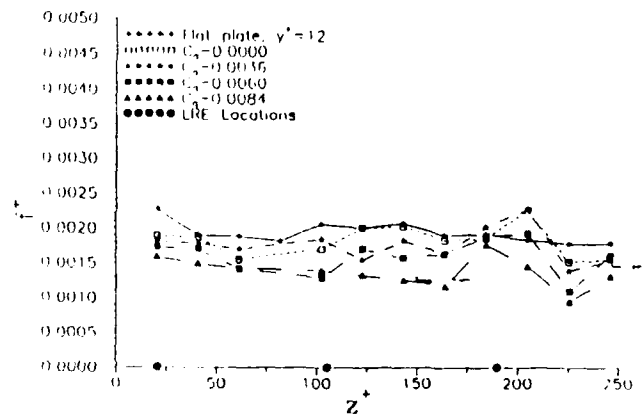

Figure 13. The VITA detection frequency with the longitudinal roughness elements and suction compared with the flat plate values.